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Effect of Environmental Factors on Free Space Propagation of Mid Infrared Quantum Cascade Laser

AmitYadav
Electronics and Communication Department
National Institute of Technology Jamshedpur,
Jamshedpur, Jharkhand, India
amityadavnitjsr@gmail.com

PriyankaYadav
Electronics Instrumentation and Control Department
YMCA University of Science and Technology
Faridabad, Haryana, India
priyankaeic@gmail.com

Anchal
Associate Professor, Master of Computer Application
Dronacharya Institute of Management & Technology
Kurukshetra, Haryana, India
anchal87mca@gmail.com

***Abstract*-In this paper we have studied the behaviour of quantum cascade laser at different wavelengths in Free Space Optics Line of Sight links under different environmental conditions including fog, haze, and under different visibility conditions. Today there is growing demand for high speed data transmission in which FSO is one of the promising technologies which can serve as an alternative but it is severely affected by atmospheric effects. We have found that it is advantageous to use quantum cascade laser (λ=10micron) in moderate fog conditions as scattering coefficient is reduced by approximately 70%.**

***Keywords*—Quantum Cascade Laser, Mie Scattering, Aerosol Particle, Scattering Coefficient**

I. INTRODUCTION

FSO is a line of sight laser communication through the air. To date the primary barrier to commercial uptake of this technology has been the limitation imposed by adverse weather, particularly fog, which restricts conventional near infrared region (NIR) laser system throughput in the air. The quantum cascade laser (QCL) provides key optical emission wavelength in the mid infrared region (MIR) that overcome many of these problems and thereby increase communication robustness. Free-Space Optical (FSO) linksinvolve the transmission, absorption and scattering of light by the Earth's atmosphere. The atmosphere interacts with light due to the composition of the atmosphere which, under normal conditions, consists of a variety of different molecules and small suspended particles called aerosols. This interaction produces a wide variety of optical phenomena namely selective attenuation of radiation that propagates in the atmosphere, absorption at specific optical wavelengths due to the molecules and aerosol particles, different types of scattering depending upon the size of scattering particle. We have discussed these phenomena in coming sections.

II. MOLECULAR ABSORPTION ATTENUATION

Molecular absorption attenuation results from an interaction between the radiation and atoms and molecules of the medium (N_2, O_2, H_2, H_2O, CO_2, O_3, Ar, etc.). The absorption coefficient depends on the type of gas molecules and on their concentration. Molecular absorption is a selective phenomenon which results in the spectral transmission of the atmosphere presenting transparent zones, called atmospheric transmission windows, and opaque zones, called atmospheric blocking windows[4].

The global transmission windows in the optical range are as following:

Visible to very near IR:	from 0.4 to 1.4 µm,
Near IR or IR I:	from 1.4 to 1.9 µm and 1.9 to 2.7 µm,
Mean IR or IR II:	from 2.7 to 4.3 µm and 4.5 to 5.2 µm.
Far IR or IR III:	from 8 to 14 µm.
Extreme IR or IR IV:	from 16 to 28 µm.

Since wavelengths are chosen to fall inside transmission windows within the atmospheric absorption spectra, hence the contributions of absorption to the total attenuation coefficient are very small.

III. MOLECULAR SCATTERING ATTENUATION

The scattering by atmospheric gas molecules (Rayleigh scattering) contributes to the total attenuation of electromagnetic radiation. It results from the interaction of light with particles whose size is smaller than its wavelength.

The molecular composition of the atmosphere allows us to obtain an approximate value of $\beta_m(\lambda)$[4].

$$\beta_m(\lambda) = A\lambda^{-4} \qquad (1)$$

$$A=1,09*10^{-3}\frac{P}{P_0}\frac{T}{T_0}\,(km^{-1}\mu m^4) \qquad (2)$$

Where:
P (mbar) is the atmospheric pressure and P_0 = 1013 mbar,
T (K) is the atmospheric temperature and T_0 = 273.15 K.

The result is that molecular scattering is negligible in the infrared waveband.

IV. ATMOSPHERIC ATTENUATION DUE TO AEROSOL

Aerosols are extremely fine solid or liquid particles suspended in the atmosphere with very low fall speed under gravity. Their size generally lies between 10^{-2} to 100 µm. Aerosols influence the conditions of atmospheric attenuation due to their chemical nature, their size and their concentration[4].

A popular analytic size distribution model for atmospheric particles is the Deirmendjian modified gamma distribution[5].

$$n(r) = ar^{\alpha}e^{-br^{\gamma}} \quad 0 < r < \infty \qquad (3)$$

Which vanishes at r =0 and r = ∞ where n = particle concentration per unit volume per unit increment of the radius (cm^{-3}), r = radius of the particle (µm). For a given drop-size distribution, a, α, b, y = positive and real constants, and α is an integer and are related to physical property of the medium. A normalized drop-size distribution for three fog and two haze particle distributions are shown in Figure (1) and Figure (2) respectively.

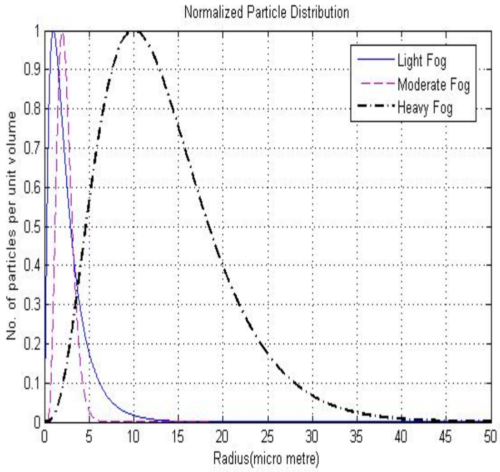


Fig.1. Fog Particle Distribution

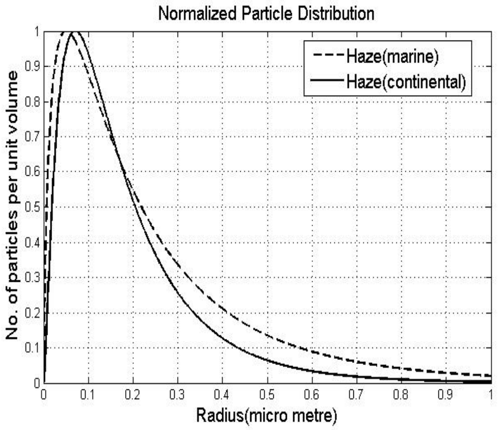


Fig.2. Haze Particle Distribution

Mie using electromagnetic theory derived theoretical expressions for the scattering and extinction efficiency[5]. An available code can be found on the Internet. Figure 3 and 4 shows calculated-scattering and absorption efficiencies as a function of particle radius for particles made of water (index of refraction = 1.33) .As from the figure it is clear that absorption efficiency is very small, so the contribution of aerosol absorption in overall attenuation can be neglected.

So if the particle size distribution is known we can calculate scattering cross section using Mie theorem and then calculate attenuation coefficient by this equation[5].

$$\sigma \cong \beta_n = \int_0^{\infty} \pi r^2 Q_{sca}(r)n(r)dr \qquad (4)$$

From the figure shown below we can see that for aerosol particles, less than 5 µm in a radius, 10µm light is the least affected by atmosphere compared

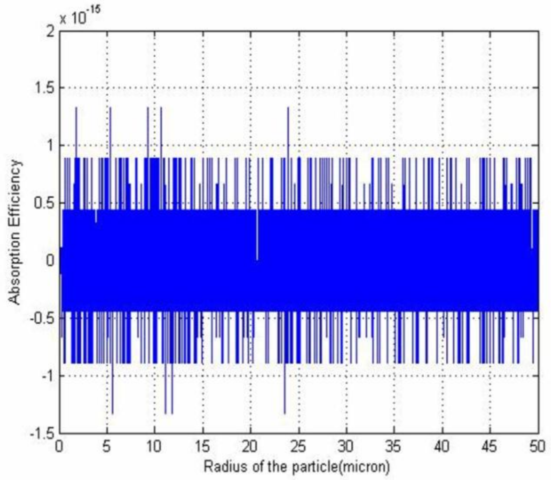


Fig.3. Absorption Efficiency of Aerosol Particles

with shorter wavelengths, but as size the of aerosol particle increases there is no significant difference in atmospheric attenuation among all the wavelength. Scattering coefficient for each wavelength was calculated using Mie theorem and results were as expected but the scattering coefficient in case of moderate fog was decreased by almost 70%.(see Table 1.)

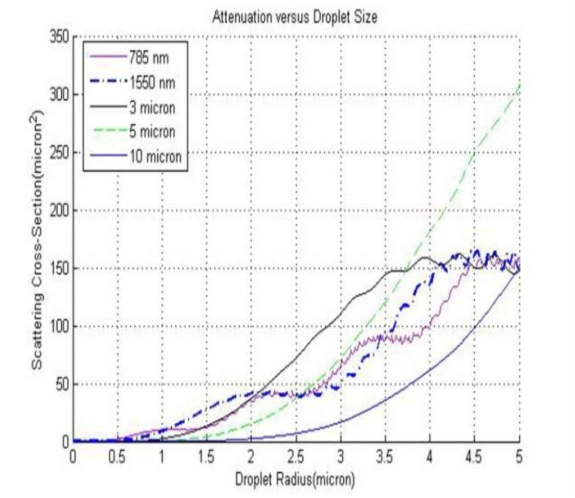


Fig.4. Attenuation in case of smaller size particle

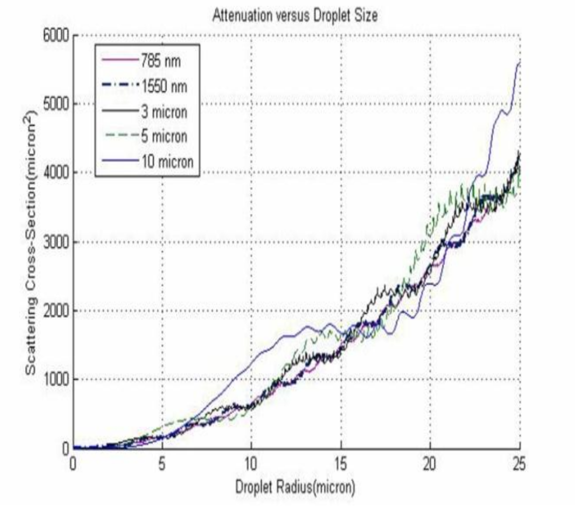


Fig.5. Attenuation in case of larger size particle

V. SCATTERING COEFFICIENT IN TERMS OF VISIBILITY

An aerosol's concentration, composition and dimension distribution vary temporally and spatially, so it is difficult to predict attenuation by aerosols. Although their concentration is closely related to the optical visibility, there is no single particle dimension distribution for a given visibility. Visibility is a concept defined for meteorological purposes. It is characterized by the transparency of the atmosphere, estimated by a human observer. It is measured according to the meteorological optical range (or runway visual range), the distance that a parallel beam of luminous rays must travel through the atmosphere until its intensity (or luminous flux) drops to 0.05 times its original value. It is measured using a transmissometer or a diffusiometer. The scattering coefficient β_n can be expressed according to visibility and wavelength by the following expression[4], [2], [1]:

$$\beta_n = \frac{3.91}{V}\left\{\frac{\lambda_{nm}}{550_{nm}}\right\}^{-Q} \qquad (5)$$

Where:

V is the visibility in km,

$\lambda_{nm}$is the wavelength (in nm),

Q is a factor which depends on the scattering particle size distribution [KRUSE, 1962]:

Q - 1.6 for large visibility (V> 50 km),

Q - 1.3 for mean visibility (6 <V< 50 km),

Q - 0.585 $V^{1/3}$ for low visibility (V< 6 km).

A recent study [KIM, 2001] proposes another expression for the parameter Q. This expression, not yet proven experimentally, is:

Q = 1.6 if V > 50 km
Q = 1.3 if 6 km <V < 50 km
Q = 0.16*V +0.34 if 1 km <V < 6 km
Q = V - 0.5 if 0.5 km <V < 1 km
Q = 0 if V <0.5 km

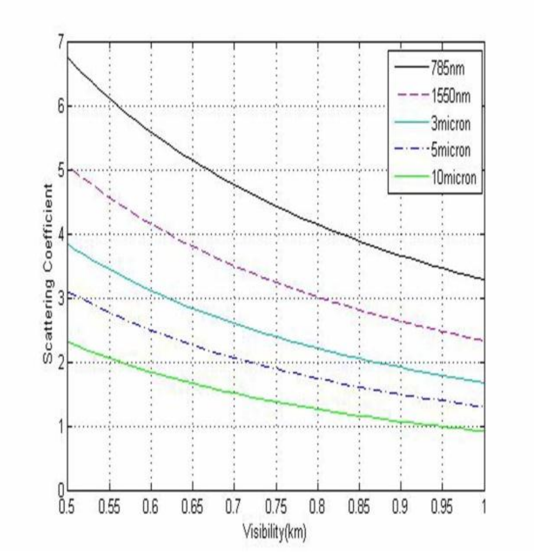
When molecular and aerosol absorption coefficients as well as the Rayleigh scatter coefficient have low values, the extinction coefficient can be given by the following equation:

$$\sigma \cong \beta_n = \frac{3.91}{V}\left\{\frac{\lambda_{nm}}{550_{nm}}\right\}^{-Q} \qquad (6)$$

Figure below give the scattering coefficient as a function of visibility. It is clearly shown from the figure that when visibility is between 500 meter to 2 km , atmospheric attenuation gets higher as wavelength decreases. But during adverse weather condition there is no effect of wavelength on atmospheric attenuation i.e. for visibility less than 500m and also for clear weather conditions there is almost no effect of wavelength on attenuation.

Table 1. Scattering Coefficient for Different environment conditions.

Distribu-tion Type	Modal Radius (μm)	a	α	γ	b	μ(km^{-1}) 785nm	μ (km^{-1}) 1550nm	μ (km^{-1}) 3μm	μ (km^{-1}) 5μm	μ (km^{-1}) 10μm
Heavy Fog	10	0.027	3	1	0.3	28.5	29.5	30.4	31.6	35.3
Moderate Fog	2	607.5	6	1	3	8.86	9.71	12.6	9.32	2.70
Light Fog	1	341	2	0.5	4	1.61	1.71	1.88	1.98	1.61
Haze M (marine)	0.05	$5.3*10^4$	1	0.5	8.9	1.076	0.78	0.34	0.13	0.022
Haze L (continen-tal)	0.07	$5.0*10^6$	2	0.5	15.1	0.369	0.155	0.038	0.0095	0.00096



Fig

.6. For very low visibility

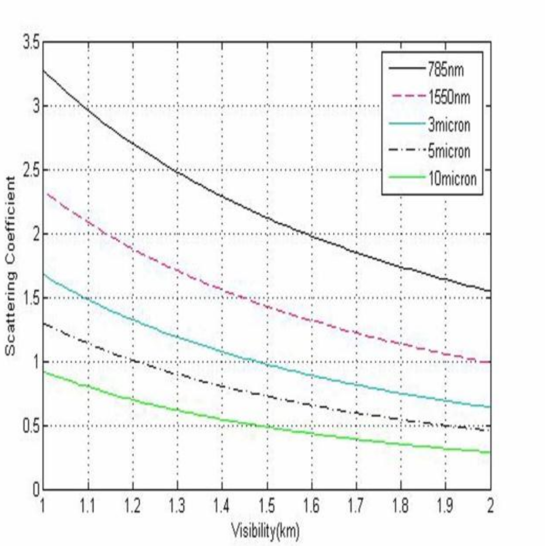


Fig.7. For moderate visibility

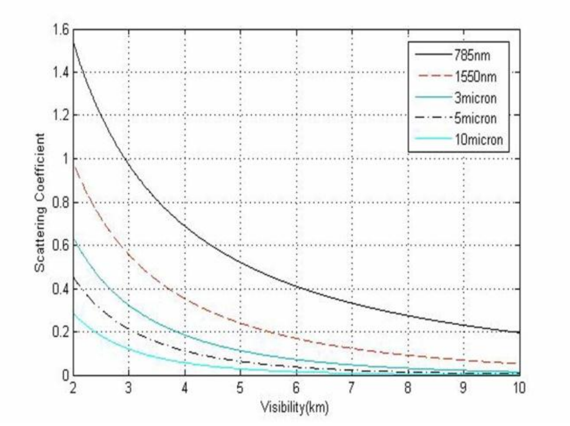


Fig.8. For Clear Sky

VI. CONCLUSION

Free-space optical communication through atmosphere turbulence is now under active research. We found that effect of molecular scattering, molecular absorption and aerosol absorption in total attenuation is negligible. But aerosol scattering plays a major role in attenuation and is wavelength selective depending on the size of scattering particle and wavelength of light. In this paper we have successfully simulated the free space optical propagation under various environmental conditions. We have found that it is advantageous to use MIR quantum cascade laser in moderate environmental conditions and moderate visibility conditions but using it in clear sky conditions and adverse weather have very little advantage.

VII. REFERENCE

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